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PROGRESS REPORT ON EXPLOSIVES MACHINING STUDY

By
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Investigation of machining variables' effects on explosive chip temperature.

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F O R E W O R D

1. This report contains the preliminary results of an investigation into the hazard potentials of cutting speed, depth of cut, feed rate and cutter design when machining explosives.

2. The effort reported herein was authorized and funded under the Naval Sea Systems Command Work Request N0002480WR0B087 of 1 October 1979.

Released by

W. McBride

W. McBRIDE, Director
Naval Explosives Development
Engineering Department
August 1980

Under authority of
J. A. BUCK
Commanding Officer

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PROGRESS REPORT ON EXPLOSIVES MACHINING STUDY

I. INTRODUCTION

The machining of explosives is required to produce and/or demilitarize the majority of Navy ordnance. To reduce risks, OP 5[1] provides the constraints regulating machining operations. Of prime importance are those concerning the machining variables, i.e., cutting speed, depth of cut, and tool feed rate. The cutting speed limit is considered too conservative by some; however, a fairly recent explosion while core sampling a cast plastic-bonded explosive has raised the caution flag. Considerable machining experience has been compiled on explosives with low melting point ingredients, such as TNT and wax, that impede achieving excessive temperatures in those explosives. Today's plastic-bonded explosives are designed for high temperature use, and therefore do not contain those "built-in safety valves".

This study, sponsored by the Ammunition Systems Group of the Naval Sea Systems Command, is to quantify, if possible, the hazardous effects of the machining variables.

Initiation of an explosive is a thermal phenonema where input energy, regardless of its form (impact, shock, etc.), is converted to heat, increasing internal energy until an activation level is reached - an exothermic chemical reaction occurs providing heat for additional reactions to occur, continuing the cycle, until a "runaway" condition exists.

Therefore, if the effect of a machining variable is to raise explosive temperature, then it has increased the possibility for initiation to occur. Consequently, it was decided that an investigation of the heat producing effects of the machining variables, as manifested by explosive temperature increases, would provide the most beneficial insight as to their hazard-producing potentials.

Normally, maximum temperature occurs in the relatively small mass of the explosive chip due to rupture along its shear plane and subsequent sliding across the cutter face. Since it is difficult to measure temperature at that point without disturbing normal chip flow, plus the desirability for interchangeable cutter use, a thermocouple-instrumented spacer that supports the cutter insert (Figure 1) was used as an indirect measure of chip temperature.

Even though thermocouple temperature is a function of several variables, i.e., chip temperature, area of the chip-cutter interface, and heat conduction path through the cutter, it should serve as a relative measure of heat produced in the chips of various materials being machined.

[1]NAVSEA OP 5, Ammunition and Explosives Ashore (Safety Regulations for Handling, Storing, Production, Renovation and Shipping)

II. PROCEDURE

A lathe turning operation with a single pointed cutter, no coolant, and easy chip removal was selected as the optimum for isolating the cutting variables' effects. Two types of tungsten carbide cutter inserts were used to demonstrate the effects of positive and negative back rake cutters, while providing uniformity in cutter shape and surface characteristics. A thermocouple installed in the cutter seating spacer of the tool holder assured consistency in monitoring the same discreet area of the underside of the clamped-in cutter (Figure 1).

The initial effort was to evaluate the effects of cutting speed, depth of cut, tool feed rate and cutter configuration on the thermocouple temperature for various inert materials. Ranges of the machining variables were selected to suit the eventual explosive study, and were:

50 - 300 surface feet per minute cutting speed (CS).

.005 - .096 inch depth of cut (Dp).

.002 - .020 inch per revolution feed (Fd).

Preliminary trials of the test setup on inert materials disclosed two very fortuitous aspects of the thermocouple location; first, it was very sensitive to changes in the machining variables, and secondly, for any set of machining conditions a substantially constant or stabilized temperature would be maintained. The temperature rise, Δt (stabilized minus ambient), provided the measurable effect of the machining variables.

A statistical method, the two-level factorial design, provided the means for determining the effect of cutting speed, depth of cut, and feed rate for each cutter configuration in the minimum number of experiments. Analysis of those results led to a procedure for developing a mathematical relationship between the variables and Δt for each of the materials studied.

The inert study provided a convenient means of verifying procedures and establishing a reference base of data for materials of widely differing physical properties.

To date, machining experiments have been completed for five explosives - TNT, HBX-1, PBXN-3, PBXN-104, and PBXN-105. Equations, relating thermocouple temperature to the machining variables for each type cutter, have been derived. All of the relationships are presented in Table I.

To better illustrate the comparative effects of those equations, the maximum explosive machining limits permitted by OP 5, i.e., 210 surface feet per minute cutting speed, 0.188 inch depth of cut, 0.035 inch per revolution feed, were used to calculate Δt's for each material. These are shown in Table II.

The temperature equations established for the metals are intended to provide a general basis for comparison of materials. The machinability of metals can be drastically affected by composition, heat treatment, work hardening, etc., and is a very complex subject, not to be explored here.

Although the temperature of the explosive chip is the primary concern, comparison of the thermocouple temperatures achieved by machining various materials at the same conditions should provide a measure of the relative heat-generating, and therefore hazard-potential, characteristics.

Lacking a means of directly measuring the chip-cutter interface temperature, a method for roughly estimating it was developed. By using 93 degrees Celsius (°C) and 316°C temperature-indicating crayons, and deducing that interface contact area is related inversely to chip temperature, the following equations were derived:

(1) For metals, $$t_c = \frac{\Delta t}{2\ Dp + .01}$$

(2) For non-metals, $$t_c = \frac{1.75\ \Delta t + 22}{1.75\ Dp + 1}$$

Insertion of the standard machining conditions and calculated Δt's of Table II in Eqs. (1) and (2) permitted the calculation of estimated chip temperatures also listed in Table II.

An example of the method for determining experimental machining conditions and subsequent derivation of the Δt equations are shown in Table III and Figure 2. The ranges of each variable, x_1, x_2, and x_3, were 100 to 300 surface feet per minute cutting speed, 0.016 to 0.048 inch depth of cut, and 0.005 to 0.020 inch per revolution feed, respectively. The plus or minus signs for those variables in the matrix determine whether the high or low limit value of the range will be used for each experiment. Δt's, provided by the temperature traces, are recorded in Table III.

The effect of each variable and their interaction is found by taking the arithmetic sum for each column (assigning the plus or minus value to each test number Δt). Dividing each columnar total by the number of test runs, eight in this instance, provides a measure of the effect of each variable and their interactions (only positive values have significance). Assuming the total effect of the variables accounts for the range of Δt values produced, proportionate values of that range are calculated for each. These values are then divided by the range of their respective variables to get a per unit of measure change. Inserting these values in

(3) $\Delta t = a \times CS + b \times Dp + c \times Fd + d \times CS \times Dp \ldots + K$

and solving for each test condition provides the means for determining the constant, K.

III. DISCUSSION OF RESULTS

The thermocouple-instrumented spacer in the tool holder has proven to be a very satisfactory means of monitoring the heat produced in the cutter-chip interface, since it is surprisingly sensitive to machining conditions, does not interfere with chip travel, and facilitates the replacement of cutter inserts.

The temperature rise equations for the various materials are easily verified due to the small number of trials required by the two-level factorial designed experimental method.

The Δt values, at standard conditions, shown in Table II, appear representative of the expected relative energies required to machine those materials, thus lending credence to this method of evaluating them. There are substantial differences in the heat-production characteristics of the explosives while being machined at the same cutting speed, depth of cut and feed rate. This is shown by the range of thermocouple Δt's, from a low of 10°C for TNT, to three times that for PBXN-104. Estimated chip temperatures would be approximately 30°C and 63°C, respectively.

The relative effects of each of the variables, and their interplay, on Δt remained fairly constant throughout the gamut of materials investigated. Depth of cut exerted the strongest effect, followed by cutting speed and feed rate, with their ratios of magnitude being roughly 2.2:1.9:1.0, respectively.

The "worst case" explosive, PBXN-104, results in a Δt of 32°C when machined with a positive rake cutter at the OP 5 machining limits, as shown in Table II. If the depth of cut were increased from 0.188 inch to 0.25 inch, Δt would increase to 41°C, and calculated chip temperature to 65°C.

It must be remembered, however, that although useful for assessing the relative hazards of machining various materials, a Δt of the implanted thermocouple may be attributable to a high temperature explosive chip making very little surface contact with the cutter, or a lower temperature chip with considerable surface contact. Explosive chip temperature should be the basis for assessing specific hazardous machining conditions. Determining chip temperature through analysis of a very complex heat transfer situation would be very difficult, so empirical solutions from a few "known" conditions were developed. Hopefully, it may be refined and verified by future experiments.

IV. OBSERVATIONS

This study, to date, has achieved the following:

- The machining variables' effects have been related to explosive temperature, an optimum indicator of its chemical stability or hazard potential.

- The simplicity of the instrumentation and the proficiency of the statistically designed test method have enabled the accumulation of a considerable amount of meaningful data with relative ease in a short period of time.

- Expression of the variables' temperature effects in equation form has negated the need for describing them in cumbersome, less effective, alternate methods such as families of graphs, etc.

- Comparison of the Δt's achieved by various explosives under the same machining conditions provides a measure of the relative hazard potentials of those materials.

V. CONCLUSIONS

The explosive machining limits must allow for other than ideal conditions. Instances where foreign materials, broken tools, and inadvertent cutting of warhead hardware have occurred in the past without incident while machining the older, "safer" explosives; they can be expected to recur. Whether the new plastic-bonded explosives will survive that type abuse has not been established as yet due to the relatively small quantities of cased PBX's machined to date.

This study provides evidence that an appreciably more hostile environment is produced while machining PBXN-104 as compared to TNT. The Δt equations provide a means for calculating increased machining variables' limits for TNT to raise it to a comparable risk level. The relative insensitivity to initiation of TNT would further support such a move, if desired.

Lack of experience at the increased hazard level, plus the confusion resulting from tailored machining limits, would make such a move inadvisable at this time.

The mechanics of explosive initiation is not an exact science. Avoiding accidental initiations requires good judgement based upon experience, sensitivity testing, and a knowledge of the hazard potential of the environment to which explosives will be exposed. Many additional explosive compositions are planned for study in an attempt to better define the environmental hazards they will be subjected to while being machined.

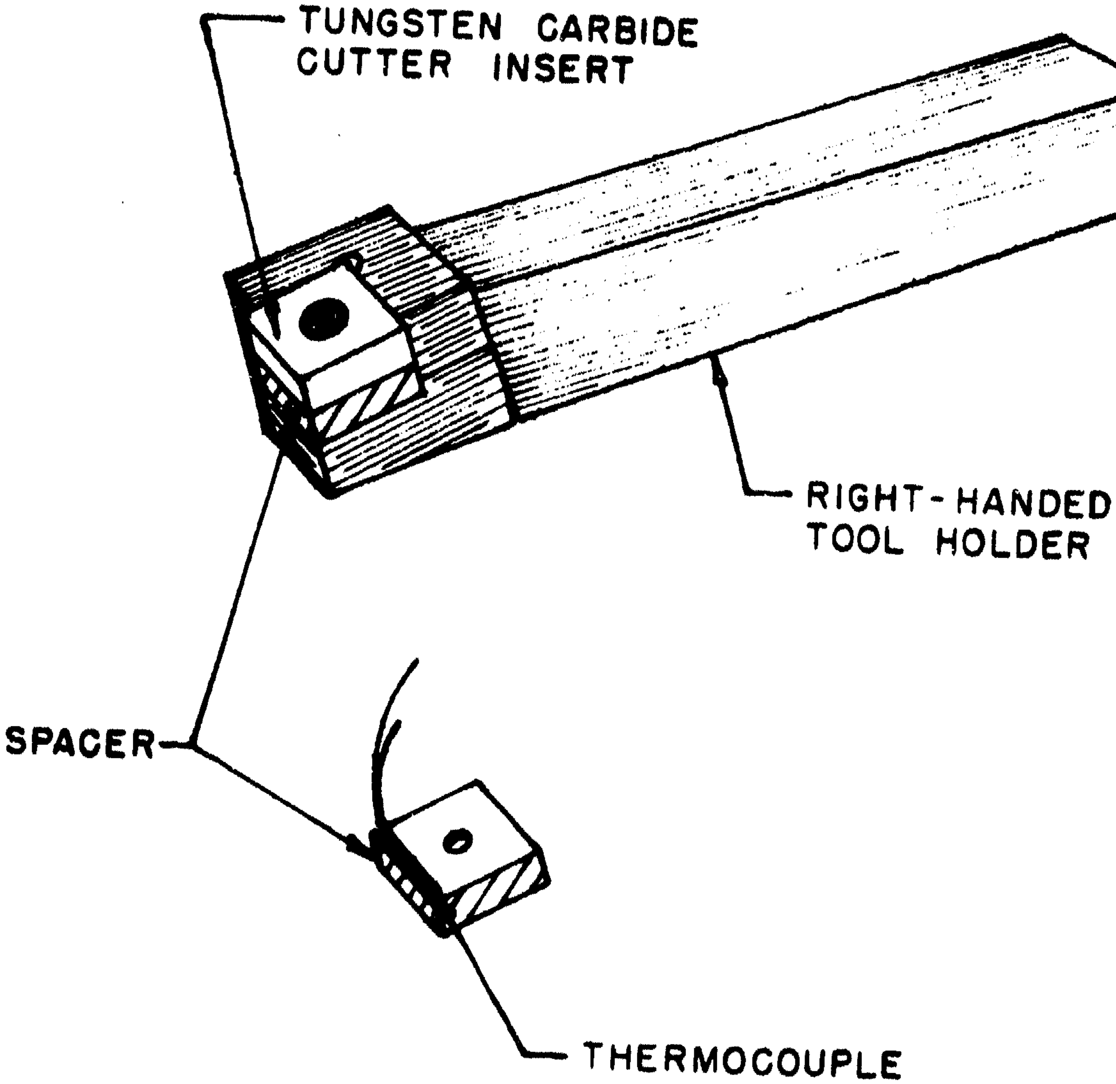

FIGURE 1
CUTTER ASSEMBLY AND
TEMPERATURE SENSOR LOCATION

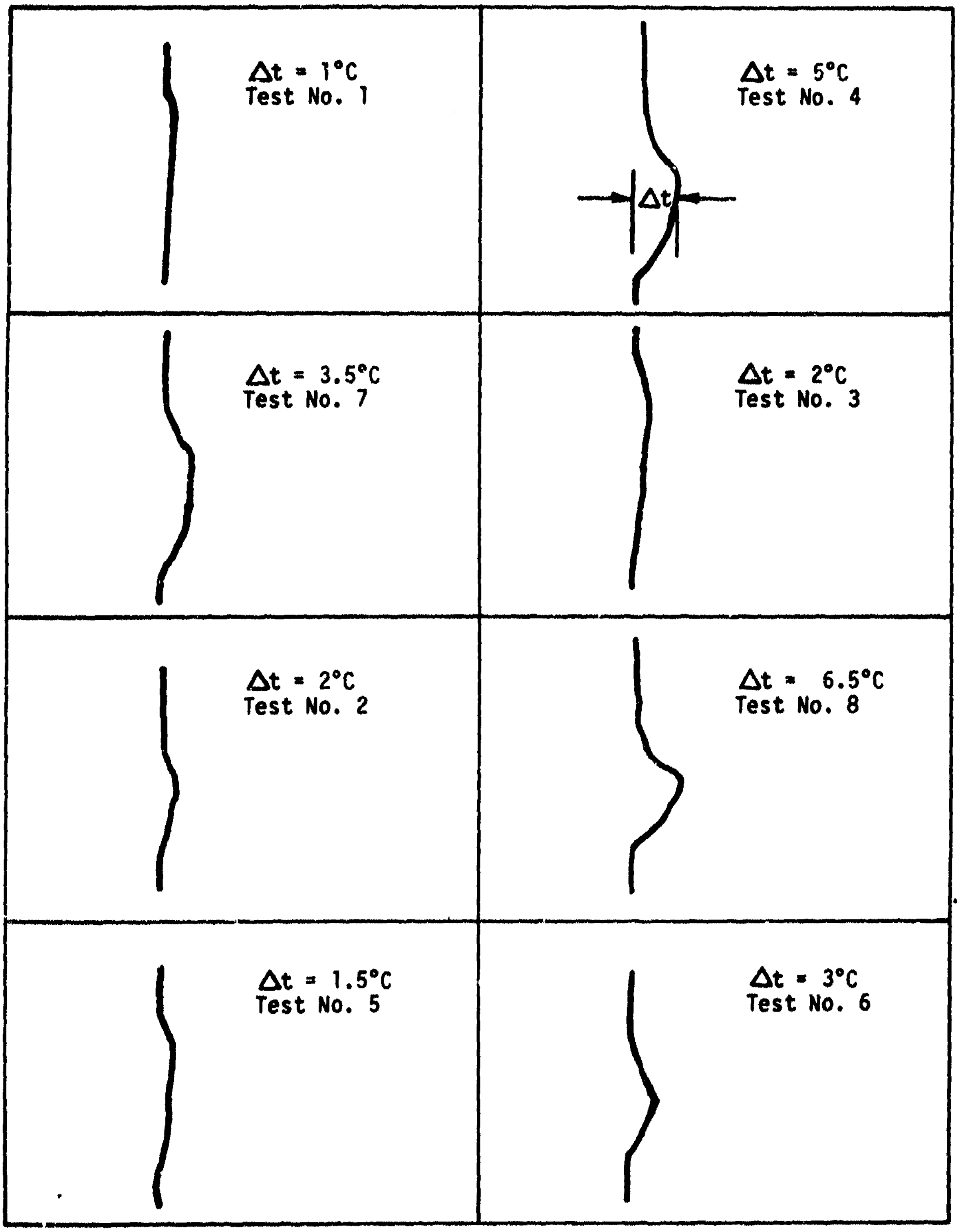

FIGURE 2. LATHE TURNING EXPERIMENT - TEMPERATURE TRACES FOR HBX-1

TABLE I. EQUATION COEFFICIENTS

Material	Back rake	a	b	c	d	e	f	g	K
Inert:									
	Pos	0.20	1625	4310	2	...	40,000	...	-23
Airdi Steel	Neg	0.48	1420	6520	...	4	34,800	...	-35
	Pos	0.13	1415	3535	2	4	...	...	-18
1020 Steel	Neg	0.20	1855	5120	2	...	...	...	-20
	Pos	0.08	1175	2450	...	...	...	...	...
Berylium Copper	Neg	0.08	2170	3500	...	...	36,800	...	-2
	Pos	0.08	540	2727	0.3	...	14,200	...	-15
6061 Aluminum	Neg	0.11	616	3913	...	...	12,858	...	-16
	Pos	0.06	250	300	...	...	5,780	22	...
Velostat	Neg	0.04	220	520	0.1	...	2,200	...	-3
	Pos	0.07	390	670	0.2	0.7	...	...	-8
PVC	Neg	0.06	34	825	...	1.2	...	23	-6
PBXN-104	Pos	0.06	310	580	0.1	0.4	...	...	-8
Simulant	Neg	0.03	425	630	0.1	...	1,000	...	-20
	Pos	0.03	95	440	0.1	...	975	...	-3
Teflon	Neg	0.02	75	525	0.1	...	1,750	...	-2
	Pos	0.01	40	20	0.03	...	...	...	...
Filler E	Neg	0.01	56	30	0.02	...	...	...	...
Explosive:									
	Pos	0.02	125	194	0.05	...	...	...	-4
PBXN-104	Neg	0.02	129	258	0.04	...	430	...	-7
	Pos	0.02	102	74	...	0.1	...	...	-1
PBXN-3	Neg	0.02	146	62	0.05	...	...	...	-2
	Pos	0.01	88	106	...	...	...	...	-2
HBX-1	Neg	0.01	63	63	0.06	...	...	...	-2
	Pos	0.02	41	95	...	...	...	...	-2
PBXN-105	Neg	0.02	69	134	0.09	...	...	...	-3
	Pos	0.01	36	60	0.03	...	...	...	-2
TNT	Neg	0.01	36	60	0.03	...	...	...	-2

$$\Delta t = \underline{a \times CS} + \underline{b \times Dp} + \underline{c \times Fd} + \underline{d \times CS \times Dp} + \underline{e \times CS \times Fd} + \underline{f \times Dp \times Fd} + \underline{g \times CS \times Dp \times Fd} + \underline{K}$$

TABLE II. COMPARATIVE Δt AND CHIP TEMPERATURE FOR MATERIALS MACHINED AT OP 5 MAXIMUM LIMITS*

Material	Pos rake		Neg rake	
	Δt (°C)	Chip temp (°C)	Δt (°C)	Chip temp (°C)
Inert:				
Airdi Steel	818	1718	819	1721
1020 Steel	507	1065	629	1321
Berylium Copper	323	679	787	1653
6061 Aluminum	304	639	344	723
Velostat	139	200	83	126
PVC	117	171	82	125
PBXN-104 Simulant	90	135	99	147
Teflon	47	78	50	82
Filler E	12	32	15	36
Explosive:				
PBXN-104	32	59	35	63
PBXN-3	25	49	34	61
HBX-1	20	43	17	39
PBXN-105	13	34	22	46
TNT	10	30	10	30

Chip temperature, for metals, $t_c = \dfrac{\Delta t}{2\ Dp + .01}$

Chip temperature, for non-metals, $t_c = \dfrac{1.75\ \Delta t + 22}{1.75\ Dp + 1}$

*OP 5 maximum limits:

210 surface feet per minute cutting speed
0.188 inch depth of cut
0.035 inch per revolution feed

TABLE III. LATHE TURNING EXPERIMENT

MATERIAL: HBX-1

DATE OF EXPERIMENT: 2/7/80

Test No.	Cutting speed (ft/min)		Depth of cut (in.)		Dia of cut (in.)	Rotational speed (rpm)		Feed (in./rev)	Ambient temp (°C)	Stable temp (°C)	Actual Δt (°C)	Calculated Δt (°C)
	Target	Actual	Target	Actual		Target	Actual					
5	100	93	.016	.016	6.336	60	56	.020	18.5	20	1.5	1.3
2	300	280	.016	.016	6.336	180	169	.005	18.5	20.5	2	2.4
7	100	92	.048	.048	6.304	60	56	.020	18.5	22	3.5	3.5
1	100	93	.016	.016	6.336	60	56	.005	18.5	19.5	1	.3
6	300	280	.016	.016	6.336	180	169	.020	18.5	21.5	3	3.3
8	300	279	.048	.048	6.304	181	169	.020	18.5	25	6.5	5.9
3	100	92	.048	.048	6.304	60	56	.005	18.5	20.5	2	2.5
4	300	279	.048	.048	6.304	181	169	.005	18.5	23.5	5	4.9

CUTTER RAKE: NEG

Δt = .01 CS + 63 Dp + 63 Fd + .06 CS x Dp -2

Δt RANGE: 5.5

Test No.	CS x_1	Dp x_2	Fd x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	Δt
1	-	-	-	+	+	+	-	1
2	+	-	-	-	-	+	+	2
3	-	+	-	-	+	-	+	2
4	+	+	-	+	-	-	-	5
5	-	-	+	+	-	-	+	1.5
6	+	-	+	-	+	-	-	3
7	-	+	+	-	-	+	-	3.5
8	+	+	+	+	+	+	+	6.5

EFFECTS	COEFF
$x_1 = 1.06 \div 3.25 \times 5.5 \div (200)$	= .01
$x_2 = 1.19 \div 3.25 \times 5.5 \div (.032)$	= 63
$x_3 = 0.56 \div 3.25 \times 5.5 \div (.015)$	= 63
$x_1x_2 = 0.44 \div 3.25 \times 5.5 \div (12.8)$	= .06
$x_1x_3 = 0.06$	
$x_2x_3 = 0.19$	
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